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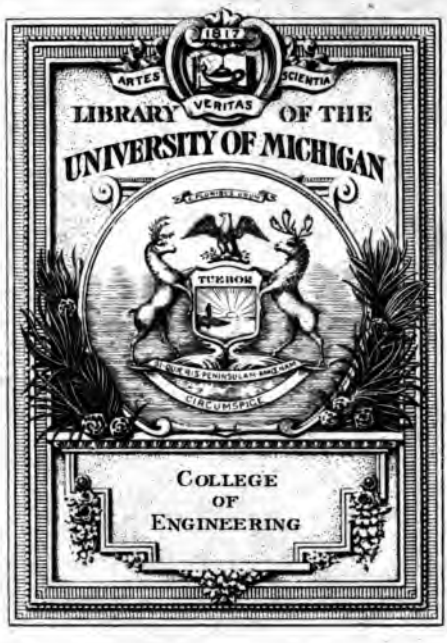
The Treatment of Steel

Miller Metcalf and Parkin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ILLUSTRATED BY
C.W.ERBY
ROOM 78 MAJOR BLK CHICAGO.

THE

TREATMENT OF STEEL.

A SERIES OF CIRCULARS

ON

HEATING, ANNEALING, FORGING AND TEMPERING,

ISSUED BY THE

CRESCENT STEEL WORKS.

Crescent steel co.

PITTSBURGH:
MILLER, METCALF & PARKIN.
1881.

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PREFACE.

FROM time to time our friends ask of us questions concerning steel, its correct treatment and management, and we have therefore thought it proper to combine in one form circulars issued by us in previous years. At the same time we add some new and, we hope, interesting matter.

We trust that it may be accepted as an effort on our part to assist in overcoming difficulties connected with the working of steel.

Many will find in it nothing new; others may be able to select something of interest and profit.

M. M. & P.

PITTSBURGH, July 1, 1881.

THE TREATMENT OF STEEL.

AN English steel manufacturer remarks: "We do not analyze for carbon because we find by long experience that the eye can judge of the percentage of carbon in an ingot of cast steel of the highest tempers from the appearance of the fracture more accurately than the chemist can ascertain by any method of analysis hitherto discovered."

We do not indorse this as a whole, but to show the reliability of "inspection by the eye" we give the result of tests made in 1874 and 1875.

In April, 1874, we selected eight ingots, by our numbers, from the ingots as they were piled up for use. The figures in the second column show the amounts of carbon in these eight ingots as determined by analysis.

In March, 1875, twelve ingots were selected in the same way, one being below the series of eight and the others being within the limits of the eight, Nos. 5, 7 and 10 being interpolations.

It will be seen that the carbon runs up with the numbers

without a break, thus proving by careful analysis that our methods were careful and reliable.

The mean difference in carbon is only seven-hundredths of one per cent. As there is no possibility of a skillful and careful person mistaking any one of these numbers for another, our patrons can judge for themselves of the probability of receiving steel of uniform temper and properly adapted to the work to be done.

The structure of the ingot is invariably the same for the same amount of carbon, and the observance of this rule is the steel maker's guide and the steel user's safety.

Analyses made by Prof. John W. Langley, University of Michigan, Ann Arbor, Michigan:

No.	Carbon. March, 1875.	Carbon. April, 1874.	Carbon. Mean of the two preceding columns.	Differences.	Iron by Difference.
1	.302	....	.302	....	99.614
2	.490	.404	.447	.145	99.454
3	.529	.599	.564	.117	99.363
4	.649	.789	.719	.155	99.270
5	.801	....	.801	.082	99.119
6	.841	.856	.848	.047	99.085
7	.867	....	.867	.019	99.044
8	.871	.867	.869	.002	99.040
9	.955	.939	.947	.078	98.900
10	1.005	....	1.005	.058	98.860
11	1.058	1 036	1.047	.042	98.752
12	1.079	1.116	1.097	.050	98.753
Mean differences.	.071	.102	....	.072	.....

The figures in this table are fractions of one per cent.

ON ANNEALING.

OWING to the fact that the operations of rolling or hammering steel make it very hard, it is frequently necessary that the steel should be annealed before it can be conveniently cut into required shapes for tools.

Annealing or softening is accomplished by heating steel to a red heat and then cooling it very slowly, to prevent it from getting hard again.

The higher the degree of heat, the more the steel will be softened, until the limit of softness is reached when the steel is melted.

It does not follow that the higher a piece of steel is heated, the softer it will be when cooled, no matter how slowly it may be cooled; this is proved by the fact that an ingot is always harder than a rolled or hammered bar made from it.

Therefore, there is nothing gained by heating a piece of steel hotter than a good bright cherry red; on the contrary, a higher heat has several disadvantages:

FIRST—If carried too far, it may leave the steel actually harder than a good red heat would leave it.

SECOND—If a scale is raised on the steel, this scale will be harsh, granular oxide of iron, and will spoil the tools used to cut it. It often occurs that steel is scaled in this way, and then because it does not cut well, it is customary to heat it again, and hotter still, to overcome the trouble; while the fact is, that the more this operation is repeated, the harder the steel will work, because of the hard scale and the harsh grain underneath.

THIRD—A high scaling heat, continued for a little time, changes the structure of the steel, destroys its crystalline property, makes it brittle, liable to crack in hardening, and impossible to refine.

Again, it is a common practice to put steel into a hot furnace at the close of a day's work, and leave it there all night. This method always gets the steel too hot, always raises a scale on it, and worse than either, it leaves it soaking in the fire too long; and this is more injurious to steel than any other operation to which it can be subjected.

A good illustration of the destruction of crystalline structure by long continued heating may be had by operating on chilled cast iron.

If a chill be heated red hot and removed from the fire as soon as it is hot, it will, when cold, retain its peculiar crystalline structure; if now it be heated red hot, and left at a moderate red for several hours; in short, if it be treated as steel often is, and be left in a furnace over night, it will be found, when cold, to have a perfect amorphous structure, every trace of chill crystals will be gone, and the whole piece will be non-crystalline gray cast iron. If this is the effect upon coarse cast iron, what better is to be expected from *fine cast steel?*

A piece of fine tap steel after having been in a furnace over night will act as follows:

It will be harsh in the lathe and spoil the cutting tools.

When hardened it will almost certainly crack; if it does not crack it will have been a remarkably good steel to begin with. When the temper is drawn to the proper color and the tap is put into use, the teeth will either crumble off or crush down like so much lead.

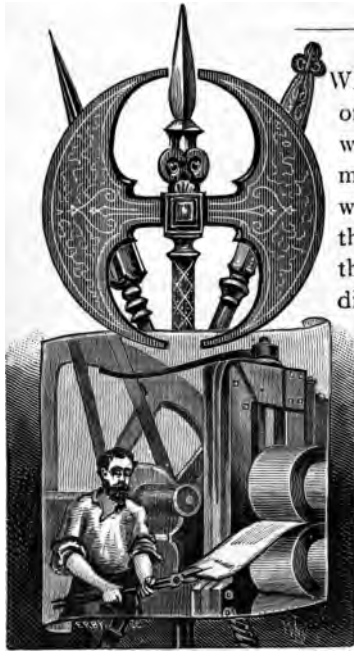
Upon breaking the tap the grain will be coarse and the steel brittle.

To anneal any piece of steel, heat it red hot; heat it *uniformly* and heat it *through*, taking care not to let the ends and corners get too hot.

As soon as it is hot take it out of the fire, the sooner the better, and cool it as slowly as possible. A good rule for heating is to heat it at so low a red that when the piece is cold it will still show the blue gloss of the oxide that was put there by the hammer or the rolls.

Steel annealed in this way will cut very soft; it will harden very hard, without cracking, and when tempered it will be very strong, nicely refined and will hold a keen, strong edge.

ON HEATING STEEL.



OWING to varying instructions on a great many different labels, we find at times a good deal of misapprehension as to the best way to heat steel; in some cases this causes too much work for the smith, and in other instances disasters follow the act of hardening.

There are three distinct stages, or times of heating:

FIRST, for forging.

SECOND, for hardening.

THIRD, for tempering.

The first requisite for a good heat for forging is a clean fire and plenty of fuel, so that jets of hot air will not strike the corners of the piece; next, the fire should be regular, and give a good uniform heat to the whole part to be forged. It should be keen enough to heat the piece as rapidly as may be, and allow it to be thoroughly heated through, without being so fierce as to overheat the corners.

The trouble in the forge fire is usually uneven heat, and *not too high heat.* *Suppose* the piece to be forged has been

put into a very hot fire, and forced as quickly as possible to a high yellow heat, so that it is almost up to the scintillating point. If this be done, in a few minutes the outside will be quite soft and in nice condition for forging, while the middle parts will be not more than red hot. The highly heated soft outside will have very little tenacity; that is to say, this part will be so far advanced toward fusion that the particles will slide easily over one another, while the less highly heated inside parts will be hard, possessed of high tenacity, and the particles will not slide so easily over each other.

Now let the piece be placed under the hammer and forged, and the result will be as shown in Fig. 1.

FIG. 1.

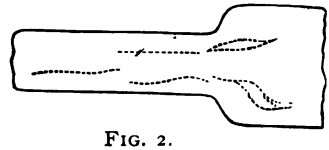


FIG. 2.

The soft outside will yield so much more readily than the hard inside, that the outer particles will be torn asunder, while the inside will remain sound, and the piece will be pitched out and branded "burned."

Suppose the case to be reversed and the inside to be much hotter than the outside; that is, that the inside shall be in a state of semi-fusion, while the outside is hard and firm.

Now let the piece be forged and we shall have the case as shown in Fig. 2. The outside will be all sound and the whole piece will appear perfectly good until it is cropped, and then it is found to be hollow inside, and it is pitched out and branded "burst."

In either case, if the piece had been heated soft all

through, or if it had been only red hot all through, it could have been forged perfectly sound and good.

If it be asked, why then is there ever any necessity for smiths to use a low heat in forging, when a uniform high heat will do as well, we answer:

In some cases a high heat is more desirable to save heavy labor, but in every case where a fine steel is to be used for cutting purposes, it must be borne in mind that *very heavy forging* refines the bars as they slowly cool; and if the smith heats such refined bars until they are soft, he raises the grain, makes them coarse, and he cannot get them fine again unless he has a very heavy steam hammer at command and knows how to use it well.

In following the above hints there is a still greater danger to be avoided: that is incurred by letting the steel lie in the fire after it is properly heated. When the steel is hot through it should be taken from the fire immediately and forged as quickly as possible.

"Soaking" in the fire causes steel to become "dry" and brittle, and does it more injury than any bad practice known to the most experienced.

By observing these precautions a piece of steel may always be heated safely, up to even a bright yellow heat, when there is much forging to be done on it; and at this heat it will weld well.

The best and most economical of welding fluxes is clean, crude borax, which should be first thoroughly melted and then ground to fine powder. Borax prepared in this way will not froth on the steel, and one half of the usual quantity will do the work as well as the whole quantity unmelted.

After the steel is properly heated it should be forged to shape as quickly as possible, and just as the red heat is leav-

ing the parts intended for cutting edges, these parts should be refined by rapid light blows, continued until the red disappears.

For the second stage of heating for hardening great care should be used, first, to protect the cutting edges and working parts from heating more rapidly than the body of the piece; next, that the whole part to be hardened be heated uniformly through, without any part becoming visibly hotter than the other. A UNIFORM heat, as low as will give the required hardness, is the best for hardening.

BEAR IN MIND, that for every VARIATION OF HEAT which is great enough to be seen there will result a VARIATION IN GRAIN, which may be seen by breaking the piece, and for every such variation in temperature there is a very good chance for a CRACK to be seen. Many a costly tool is ruined by inattention to this point.

The effect of TOO HIGH HEAT is to OPEN THE GRAIN, to make the steel COARSE.

The effect of an IRREGULAR heat is to cause IRREGULAR grain, IRREGULAR strains, and CRACKS.

As soon as the piece is properly heated for hardening it should be promptly and thoroughly quenched in plenty of the cooling medium, water, brine or oil, as the case may be.

An abundance of the cooling bath, to do the work quickly and uniformly all over, is very necessary to good and safe work.

To harden a large piece safely a running stream should be used.

Much uneven hardening is caused by the use of *too small* baths.

For the third stage of heating; to temper, the first important requisite is again UNIFORMITY. The next is time.

more slowly a piece is brought down to its temper, the better and safer is the operation.

When expensive tools, such as taps, rose cutters, etc., are to be made, it is a wise precaution, and one easily taken, to try small pieces of the steel at different temperatures, so as to find out how low a heat will give the necessary hardness. The lowest heat is the best for any steel, the test costs nothing, takes very little time, and very often saves considerable losses.

FURNACES.

WE present in this connection sketches of a cheap and handy furnace for use in a blacksmith shop, adapted especially for heating steel, and more particularly for heating steel for hardening.

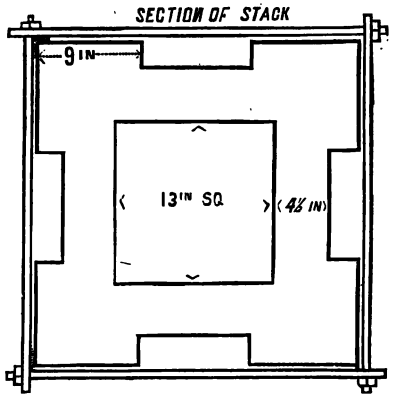
The furnace is so simple that the sketches need no explanation; for binders, ten pieces of old rail about six feet long with one end set in the ground and the tops tied by ¾ inch rods are all that is necessary, with a piece of iron about 3 × ¾ inches running around near the top, and set in flush with the bricks.

The distinctive features of this furnace are the fire bed and a good damper on the stack. In an experience of many years we have found nothing better than the Tupper grate-bar with half-inch openings. These bars set in as shown make a level, permanent bed, and give an evenly distributed supply of air to the fuel. In such a furnace as this one set of bars will last for years and remain level.

While on the subject of grate-bars we may as well say that the satisfactory and safe working of this furnace would be entirely defeated by any attempt to use either square wrought-iron bars or ordinary straight cast-iron bars. Such bars always warp, get pushed out of place, and allow a rush of air through at one place and no air at another. This causes hot and cold places in the furnace and produces

uneven heating, which is the chief source of cracking in hardening, and also the air rushing through the large holes will burn the steel. A bar must be used which will remain level and in its place, and the smaller and more numerous the openings are the better will be the result.

Clean hard coke is the only proper fuel for such a furnace and for such work. The furnace should be filled full up to the fore plate, or better, a little higher,—with coke in pieces



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no larger than an ordinary man's fist,—but the smaller the better.

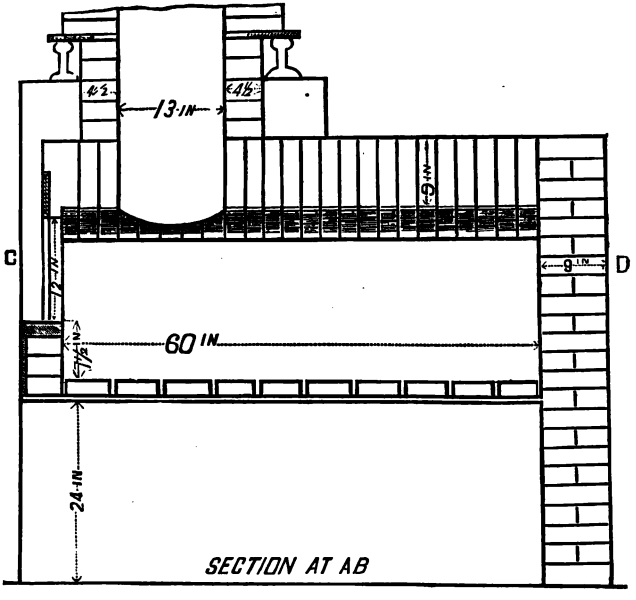
When it is used for heating for forging purposes the damper may be left high enough to run the furnace as hot as may be required,—if necessary, a welding heat can be obtained.

When used for hardening the furnace should be got as hot as is needed before the steel is put into it, then when the steel is put in the damper should be dropped down tight.

The door, which is 12 inches high and 24 inches wide, *should be nicely balanced* by a lever and weight, with a rod

in a handy place so that the operator can pull it up easily and turn over his pieces from time to time, so as to get his heat perfectly uniform.

In the clear gas of a coke fire the whole interior of a furnace can be seen easily, and every piece can be watched as



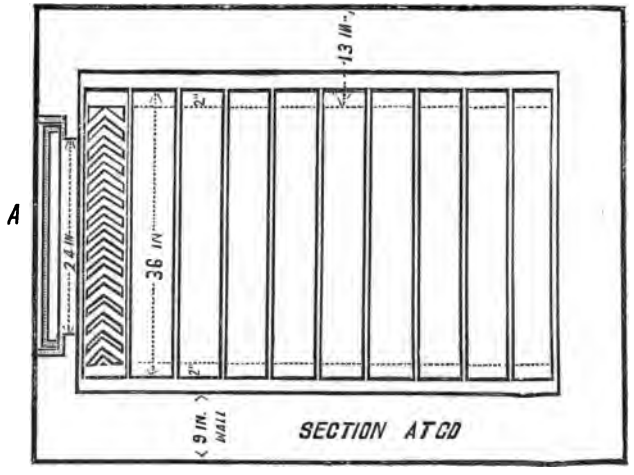
it ought to be. Time, care, watchfulness and absolute uniformity of heat are the essentials necessary for success in hardening steel.

Every large shop should have such a furnace, and should have one man trained to its use, to do the hardening and tempering for the whole shop. Such a furnace in the hands of a careful man in any railroad shop in the country would *pay for itself* every year and save the man's wages besides.

The furnace will consume very little coke at any time, and when not in use, with the damper down it will stay hot a long time and waste the coke but a trifle.

There is no more absurd nor wasteful system than that of requiring a smith at his anvil to harden and temper his work. His fire is not fit to heat in, to begin with, and he never has time to do his work properly if it were.

From such a furnace as is here described we harden all



sorts of tools, taps, small dies, large rolls, rotary shear knives, and shear knives as large as five feet long, which is the whole length of the furnace.

The steel which is tempered best is that which is the finest in the grain and the strongest. The best way to test both grain and strength is to hammer out a piece to about 1¼ × ⅛ inch, a foot or so in length, and temper to a high blue, or pigeon-wing, and when cold to break it off in little pieces with a hand hammer.

A little practice will soon enable a man to determine, first, whether he heated his piece to just the right point. The file and the appearance of the grain will determine this point. Next, when a little experience as to heat has been gained, he will know by the strength and grain whether his steel is really good, or whether it is "dry" and poor.

In every shop there are plenty of worn-out tools of all sorts in the scrap-heap; the temperer should be allowed to spend all of his leisure time in hammering these out and testing them as above. The steel will cost nothing, and the knowledge gained will pay for the time over and over again. We say to our friends again that if you will heat even the finest steel in dirty slack fires you will get dirty coats of sulphurous oxides on it, and no good results.

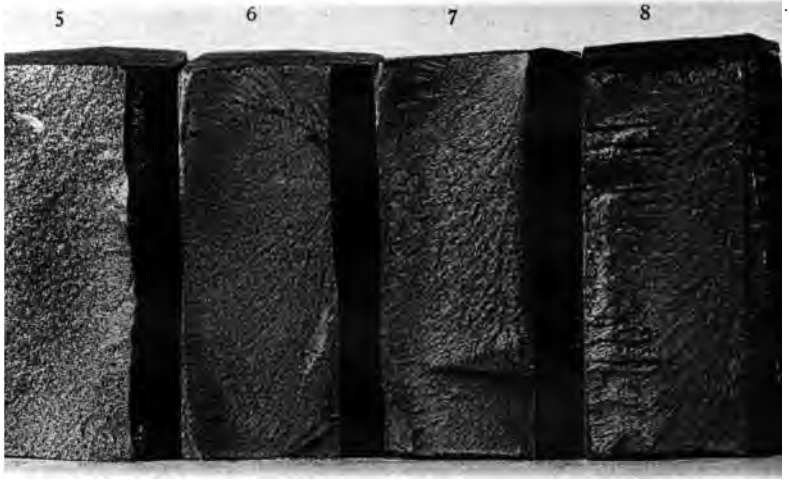
EFFECTS OF HEAT UPON STEEL.

WE now present an illustration of the effect of heat upon steel, which is a direct reproduction upon paper of the grain of the steel by means of the heliotype process.

DESCRIPTION.—Take a bar of steel of ordinary size, say about an inch by a half, and heat six or eight inches of one end to a low red heat, and nick the heated part all around the bar at intervals of half to three-quarters of an inch, until eight or nine notches are cut. This nicking is done at red heat, to determine the fractures at the nicks. Next place the end of the bar in a very hot fire and heat it white hot until it scintillates at the extreme end, leaving the other parts enough out of the fire to heat them only by conduction. Let the end remain in the fire until the last piece nicked is not quite red red-hot, and the next to the last barely red hot.

Now, if the pieces be numbered from one to eight, commencing at the outer end, No. 1 will be white or scintillating hot, No. 2 will be white hot, No. 3 will be high yellow hot, *No. 4 will be yellow* or orange hot, No. 5 will be high red

5
6
7
8



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hot, No. 6 will be red hot, No. 7 will be low red hot, No. 8 will be black hot.

As soon as heated, let the bar be quenched in cold water and kept there until quite cold. After cooling, the bar should be carefully wiped dry, especially in the notches. An examination by the file will reveal the following, if high steel has been used:

No. 1 will scratch glass, Nos. 2, 3 and 4 excessively hard, Nos. 5 and 6 well hardened, No. 7 about hard enough for tap steel, No. 8 not hardened.

In breaking off the pieces over the corner of the anvil they should be caught in a clean keg or box, to keep the fractures clean and bright.

No. 1 will be as brittle as glass, No. 2 will be nearly as brittle as glass, Nos. 3, 4 and 5 will break off easily, each a little stronger than the other, Nos. 6 and 7 will be very strong, and much stronger than No. 8, or the bar unhardened.

Place the pieces in the order of their numbers fitting the fractures, then upend each one, beginning with No. 1 and following with each in the order in which they lie, and the result will be fractures as shown so beautifully in our illustration, each differing from the other.

No. 1 will be coarse, yellowish cast, and very lustrous; No. 2 will be coarse and not quite so yellow as No. 1; No. 3 will be finer than 1 or 2, and coarser than No. 8, and will have fiery luster; No. 4, like No. 3, not quite so coarse, yet coarser than No. 8; No. 5 will be about the same size grain as No. 8, but will have fiery luster; No. 6 will be much finer than No. 8, will have no fiery luster, will be hard through and very strong. This is what is called REFINING by hardening. No. 7 will be refined and hard on the corners and edges, and rather coarser, and not quite so hard in the

middle. This is about the right heat for hardening taps, milling tools, etc., the teeth of which will be amply hard, while there will be no danger of cracking the tool. No. 8 illustrates the original grain of the bar.

In nine cases out of ten the bar will crack along the middle to the refined piece. In the illustration the crack shows very plainly in No. 4, but we have never known this crack to extend into the refined piece, although we have repeated the experiment many times. We learn from this experiment the following:

FIRST, "*a*" Any difference in temperature sufficiently great to be seen by the color will cause a corresponding difference in the grain. "*b*" This variation in grain will produce internal strains and cracks.

SECOND, Any temperature so high as to open the grain so that the hardened piece will be coarser than the original bar will cause the hardened piece to be brittle, liable to crack, and to crumble on the edges in use.

THIRD, A temperature high enough to cause a piece to harden through, but not high enough to open the grain, will cause the piece to REFINE. to be stronger than the untempered bar, and to carry a tough, keen, cutting edge.

FOURTH, A temperature which will harden and refine the corners and edges of a bar, but which will not harden the bar through, is just the right heat at which to harden taps, rose-bitts and complicated cutters of any shape, as it will harden the teeth sufficiently without risk of cracking, and will leave the mass of the tool soft and tough, so that it can yield a little to pressure and prevent the teeth tearing out. These four rules are general, and apply equally well to any quality of steel or to any temper of steel.

Steel which is so mild that it will not harden in the ordi-

nary acceptance of the term will show differences of grain corresponding to variations in temperature.

To restore any of the first seven pieces shown to the original structure as shown in No. 8, it is only necessary to heat it through to a good red heat, not to a high red, allow it to stay at this temperature for ten minutes to thirty minutes, according to the size of the piece, and then to cool slowly. If upon the first trial the restoration should be found incomplete, and the piece upon being fractured should still show some fiery grains, a second heating continued a little longer than the first would cause a restoration of fracture. This property of restoration is not peculiar to any steel, and its performance requires no mysterious agencies beyond those given above.

It should be distinctly borne in mind that a piece restored from overheating is never *quite* as good as it would have remained if it had never been abused, and we strongly advise that no occasion should ever be given for the use of this process of restoration except as an interesting experiment. The original and proper strength of fine steel can never be FULLY RESTORED after it has once been destroyed by overheating.

ON TEMPER OF STEEL.

THE word temper, as used by the steel maker, indicates the amount of carbon in steel; thus, steel of high temper is steel containing much carbon; steel of low temper is steel containing little carbon; steel of medium temper is steel containing carbon between these limits, etc. Each number of our carbon circular represents a temper, and besides these numbers we use intermediate ones, amounting to some twenty in all. As the temper of steel can only be observed in the ingot, it is not necessary to the needs of the trade to attempt any description of the mode of observation, especially as this is purely a matter of education of the eye, only to be obtained by years of experience.

The act of *tempering* steel is the act of giving to a piece of steel, after it has been shaped, the hardness necessary for the work it has to do. This is done by first hardening the piece, generally a good deal harder than is necessary, and then toughening it by slow heating and gradual softening *until it is just right for work.*

A piece of steel properly tempered should always be finer in grain than the bar from which it was made. If it is necessary, in order to make the piece as hard as is required, to heat it so hot that after being hardened it will be as coarse or coarser in grain than the bar, then the steel itself is of too low temper for the desired work. In a case of this kind, the steel maker should at once be notified of the fact, who should immediately correct the trouble by furnishing higher steel.

If a great degree of hardness is not desired, as in the case of taps, and most tools of complicated form, and it is found that at a moderate heat the tools are too hard and are liable to crack, the smith should first use a lower heat in order to save the tools already made, and then notify the steel maker that his steel was too high, so as to prevent a recurrence of the trouble. In all cases where steel is used in large quantities for the same purpose, as in the making of axes, springs, forks, etc., there is very little difficulty about temper, because, after one or two trials, the steel maker learns what his customer requires, and can always furnish it to him.

In large, general works, however, such as rolling-mill and nail factory, or large machine works, or large railroad shops, both the maker and worker of the steel labor under great disadvantages from want of a mutual understanding.

The steel maker receives his order and fills the sizes of tempers best adapted to general work, and the smith usually tries to harden all tools at about the same heat. The steel maker is right, because he is afraid to make the steel too high or too low, for fear it will not suit, and so he gives an average adapted to the size of the bar.

The smith is right, because he is generally the most hurried and crowded man about the establishment. He must forge a tap for this man, a cold nail knife for that one, and a

lathe cutter for another, and so on; and each man is in a hurry.

Under these circumstances he cannot be expected to stop and test every piece of steel he uses, and find out exactly at what heat it will harden best, and refine properly.

He needs steel that will all harden properly at the same heat, and this he usually gets from the general practice among steel makers, of making each bar of a certain temper, according to its size.

But if it should happen that he were caught with only one bar of say inch and a quarter octagon, and three men should come in a hurry, one for a tap, another for a punch, and another for a chilled roll plug, he would find it very difficult to make one bar of steel answer for all of these purposes, even if it were of the very best quality, and the chances are that he would make one good tool and two bad tools.

There is a perfectly easy and simple way to avoid all of this trouble; and that is, to write after each size the purpose for which it is wanted, as for instance: Track tools, smith tools, lathe tools, taps, dies, cold nail knives, cold nail dies, hot nails, hot or cold punches, shear knives, etc. This gives very little trouble in making the order, and it is the greatest relief to the steel maker. It is his delight to get hold of such an order, for he knows that when it is filled he will hardly ever hear a complaint.

Every steel maker worthy of the name knows exactly what temper to provide for any tool, or if it is a new case, one or two trials are enough to inform him, and as he always has all of his twenty odd tempers on hand, it is just as easy —and far more satisfactory to both parties—to have it made right as to have it made wrong.

The Sheffield manufacturer, previously referred to, calls

attention to this same experience, and very truthfully remarks:

"For many purposes, indeed, temper is of more importance than quality. Nothing is more common than for steel to be rejected as bad in quality, because it has been used for a purpose for which the temper was unsuitable. We may divide consumers of steel into three classes: First, those who use their own judgment of what percentage of carbon they require, and instruct the manufacturer to send them steel of a specified temper; second, those who leave the selection of the temper to the judgment of the manufacturer, and instruct him to send them steel for a specified purpose; and third, those who simply order steel of a specified size, leaving the manufacturer to guess for what purpose it is required. It cannot too often be reiterated of how much importance it is, when ordering steel, to state the purpose for which it is going to be used."

And again:

"You may depend upon it there is nothing so dear as cheap steel. It must be more economical to put five shillings' worth of labor upon steel that costs a shilling, to produce a tool that lasts a day, than to put the same value of labor upon steel that costs only ninepence, to produce a tool that lasts only half a day. I am sure that the system adopted by some large consumers of buying tool steel by tender is one which in too many cases defeats the object for which it was instituted, and, by lessening the price, and consequently deteriorating the quality, causes the steel bill to be lessened at the cost of the labor bill, so that extravagance instead of economy is the result. In fact, it is an illustration of the proverb about being penny wise and pound foolish."

ON GAUGES.

IN consequence of the absurdities and anomalies existing in our present system of gauges, we recommend the use of the inch as a unit of measurement.

There are in use at the present time three standard gauges, as follows:

Nos.	London. Decimals of one inch.	Stubs'. Decimals of one inch.	Brown & Sharpe's. Decimals of one inch.
1	.....	.300	.28930
2	.....	.284	.25763
3	.....	.259	.22942
4	.....	.238	.20431
5	.....	.220	.18194
6	.....	203	.16202
7	.....	.180	.14428
8	.....	.165	.12849
9	.....	.148	.11443
10	.....	.134	.10189
11	.....	.120	.09074
12	.....	.109	.08081
13	.....	.095	.07196
14	.083	.083	.06408
15	.072	.072	.05706
16	.065	.065	.05082
17	.058	.058	.04525
18	.049	.049	.04030
19	.040	.042	.03589
20	.035	.035	.03196
21	.0315	.032	.02846
22	.0295	.028	.025347

Nos	London. Decimals of one inch.	Stubs'. Decimals of one inch.	Brown & Sharpe's. Decimals of one inch.
23	.027	.025	.022571
24	.025	.022	.0201
25	.023	.020	.0179
26	.0205	.018	.01594
27	.01875	.016	.014195
28	.0165	.014	.012641
29	.0155	.013	.011257
30	.01375	.012	.010025
31	.01225	.010	.018928
32	.01125	.009	.00795
33	.01025	.008	.00708
34	.0095	.007	.0063
35	.009	.005	.00561
36	.0075	.004	.005
37	.0065	....	.00445
38	.00575	....	.003965
39	.005	....	.003531
40	.0045	....	.003144

In some cases the difference between two numbers falls as low as two thousandths of an inch, in others it is only one thousandth, etc.

It may be possible to make one gauge to any of these standards which shall be so accurate as to defy the detection of an error, and with the same care it may be possible to make a thousand such gauges; but every mechanic, and every person accustomed to making accurate measurements of the best work, knows that it is simply impossible to obtain absolute accuracy in such pieces of work when produced in large quantities, and it is impossible *commercially*, on account of the cost.

Every one knows of the wonderful accuracy of the Whitworth gauges, and also their enormous price, which makes them almost unsalable.

In regard to ordinary wire gauges, they are notoriously

inaccurate, because they cannot be made accurate and be at all salable.

In a recent case a sample under discussion measured on one gauge tight twenty-three, and on the other light twenty-four, and our customer said it was neither by his gauge.

A new gauge in our possession has its No. 23 so much larger than its No. 22 that the difference can be easily detected by the naked eye, yet No. 23 ought to be two to four thousandths smaller than No. 22.

If we were to roll No. 23 by that gauge how would our customer get what he wanted, unless his gauge accidentally contained the same blunder?

Another trouble is with the wearing of the gauges, for which there is no remedy, and we imagine that no man ever throws away a gauge because it is worn out; on the contrary, it represents an outlay of several dollars, he is used to it, he measures everything by it, and he is mad when anything does not measure to suit it. A still more serious difficulty arises from a very common mode of ordering. We frequently have orders for such a gauge "light" or "tight," "full" or "scant," "heavy" or "easy," or such a number and one-half, for instance, 15½.

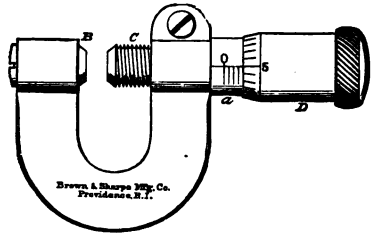
The latter is terribly confusing to a roller; he almost always takes it to mean that it is to be thicker than the whole number, and is pretty certain to make it 14½ for 15½ if he is not warned beforehand.

Then in regard to the terms "light," "easy," etc., we have, for instance, the differences between Nos. 27 and 28 in the three systems, as follows:

.00225 .002 .001554

or, two hundred and twenty-five hundred thousandths, two *thousandths, and fifteen* hundred and fifty-four millionths.

How is it possible for a roller to know just how many millionths of an inch another man, whom he never saw, means when he says No. 28 "full," or No. 27 "easy"? and how is he to guess how many thousandths of an inch the other man's gauge is wrong in its make, or how many hundredths it has worn in years of steady use? This is no fancy sketch; the above are every-day difficulties in this age, when every man knows just what he wants and will have nothing else, and yet has no better way of telling his wants than to say I want such a gauge "tight," when probably his gauge differs from every other gauge that was ever made.



There is a very easy and simple way out of this whole snarl, and that is to abandon fixed gauges and numbers altogether, and use the micrometer sheet metal gauges, which measure thousandths of an inch very accurately, and even a quarter of a thousandth may be neatly measured.

They are very simple, so that any boy of ordinary intelligence can be taught to use one in a very few minutes. They have very easy arrangements for readjustment when worn, and even when worn considerably they can be used accurately, without adjustment, by making allowance for the error in reading at the zero line.

We find that *mechanics* like to work to them, and that there is very little trouble to get sheet rolling done to within a thousandth of an inch on fine sizes.

COMPRESSED RODS.

IN 1878 we concluded to undertake the manufacture of compressed drill rods, an article hitherto never successfully made in this country; and we are now credited with the ability to furnish a product which, for quality and finish, cannot be surpassed. We are prepared to furnish the following sizes:

COMPARE GAUGE WITH EXACT SIZES GIVEN IN THOUSANDTHS OF AN INCH.

Nos.	Sizes in Decimals of 1 inch.	Nos.	Sizes in Decimals of 1 inch.	Nos.	Sizes in Decimals of 1 inch.	Nos.	Sizes in Decimals of 1 inch.
1	0.228	16	0.177	31	0.120	46	0.080
2	0.221	17	0.173	32	0.116	47	0.079
3	0.213	18	0.170	33	0.113	48	0.076
4	0.209	19	0.166	34	0.111	49	0.073
5	0.206	20	0.161	35	0.110	50	0.070
6	0.204	21	0.159	36	0.106	51	0.067
7	0.201	22	0.156	37	0.104	52	0.064
8	0.199	23	0.154	38	0.101	53	0.060
9	0.196	24	0.152	39	0.100	54	0.054
10	0.194	25	0.150	40	0.098	55	0.052
11	0.191	26	0.148	41	0.096	56	0.047
12	0.188	27	0.145	42	0.094	57	0.044
13	0.185	28	0.141	43	0.089	58	0.042
14	0.182	29	0.136	44	0.086	59	0.041
15	0.180	30	0.129	45	0.082	60	0.040

Polished "Crescent Special" Compressed Drill Rods.

From the same Bar, showing effect of Hardening.

NATURAL. REFINED. BURNT.

HELIOTYPE PRINTING CO., BOSTON.

LETTER SIZES OF WIRE.

A	0.234	H	0.266	O	0.316	U	0.368
B	0.238	I	0.272	P	0.323	V	0.377
C	0.242	J	0.277	Q	0.332	W	0.386
D	0.246	K	0.281	R	0.339	X	0.397
E	0.250	L	0.290	S	0 348	Y	0.404
F	0.257	M	0.295	T	0.358	Z	0.413
G	0.261	N	0.302				

and in addition nearly all diameters from No. Z up to 7-16 of an inch.

We guarantee these rods to show results unsurpassable by any others, if hardened at the proper heat, by which we mean just that heat which will produce the peculiar condition known as "refined by hardening." In no other condition is hardened steel at its best.

Advantages: no cracks; less change in shape and size; great tenacity, combined with extreme hardness; *certainty* insured of doing that which would be impossible with tools hardened at so high a heat as to require the temper to be drawn, to prevent breaking.

In cases where extremely hard material is to be cut, tools may be used without drawing the temper. To determine the proper heat, break from the end of a bar a short piece, keeping the fracture clean. Harden the end of the bar from which the piece was broken at a low heat. If the hardened end requires less force to break it than before, and is as coarse or coarser, the heat was *too high.* If the heat was right, the hardened piece will be stronger, and the grain will be many times finer than before hardened. By following these simple instructions, remembering that the smaller the piece operated upon, the less heat is required to harden it, and the more it will be injured if the heat is too great; after a few experi-

ments, uniform results should be obtained, as the quality of the steel is *strictly uniform.*

These rods are not made to gauges, which from lack of uniformity in size, aggravated by the natural wear in use, are a source of much trouble: but by *actual measurement*, in decimal parts of an inch, to correspond with the foregoing list. Customers adapting their work to these sizes may rest assured that orders for the same numbers will always bring them the same sizes, as nearly as it is possible for wire to be made.

In conclusion, we reproduce a paper prepared by our Mr. Metcalf, and read before the Engineers' Society of Western Pennsylvania, Pittsburgh, Pa., January 20, 1880, entitled "Why does Steel Harden?"

WHY DOES STEEL HARDEN?

THE inquiry has been pursued diligently by Prof. John W. Langley and ourselves for the past five years, and has been directed exclusively to the gathering of facts, so that as yet we have not even a theory to offer. The inquiry may be divided as follows:

1. The physical structure of steel.
2. The chemical composition.
3. The variations of structure and physical properties due to—

a.—Cooling from fusion.

b.—Effect of work, either by rolling or hammering.

c.—Effect of temperature, and of changes from one temperature to another, as shown by slow cooling or rapid cooling.

4. A statement of the various theories of hardening.
5. Some practical conclusions for workers of steel.

1. The physical structure of steel.

In this paper it is to be understood that reference is made only to cast steel.

Steel is crystalline in structure. The size, color and form of the crystals, when steel is allowed to cool without hindrance, from a state of fusion, are governed by its chemical constitution, and are mainly influenced by the quantity of *carbon* present.

2. The chemical composition of steel.

Steel is mainly an alloy, compound or mixture of iron and carbon.

Exactly which of these it may be, or whether it is a combination of two or of all three of these conditions, it is difficult to say.

Other elements, as silicon, phosphorus, sulphur, manganese, and so on, are as yet present only by sufferance, and generally it is well known that steel is better without any of them.

The range of carbon in commercial steel may be said to be from about .05 per cent to 1.75 or 2 per cent, but for some purposes of this inquiry we may look at several properties of cast iron as being useful to throw light on the subject.

3. The variations of structure and physical properties due to—

a.—Cooling from fusion—as affected by chemical composition, temperature, and rate of cooling.

The structure of steel, and of cast iron, as shown in a fresh fracture of the ingot in one case, or the pig in the other, are remarkable as always indicating the quantity of carbon present, the temperature at which the metal was poured, and the rate of cooling.

As the observation of these phenomena furnishes material for the study of a lifetime, and as they cannot be described properly without the objects themselves, only a few well known facts will be mentioned, for use in the latter part of this paper. Cast iron, when poured into iron moulds, hardens just as steel does when quenched in water; this is known as "chilling."

A chill is of silvery white color, bright luster, and consists

of elongated crystals generally normal lengthwise to the surface of the mould.

If iron contains little or no silicon, it will chill very deep, or entirely through the mass in small castings.

If much silicon be present it will not chill at all.

If a hard chill,— for instance in a hammer die,— say two inches thick of chill, be brought to a red heat, removed from the fire at once and allowed to cool slowly, it will, when broken, be found to be softened, but it will retain the marked crystalline form of the chill. This is analogous to tempered steel.

If the same chill be heated red, and kept red hot for several hours, and then cooled slowly, it will be found upon breaking to be an entirely amorphous gray cast iron; every trace of the elongated crystals of the chill will have disappeared.

This is analogous to annealed steel. This experiment is a striking example of iron and combined carbon in the one case, and of iron and graphitic carbon in the other case, as these conditions are commonly understood.

This observation is useful in understanding similar changes which occur in steel under the similar conditions of hardened, tempered and annealed steel.

Steel when cast is almost invariably poured into iron moulds, and the study of fractured ingots is very necessary to the steel-maker; but as the ingots very rarely go into the hands of the consumer without previous manipulation, it is hardly necessary to consume time in discussing the characters of the fractures, especially as it requires the actual presence of the ingots to make the description at all intelligent.

It is sufficient to say that we have here an unvarying record of the completeness or incompleteness of the fusion of

the rate and temperature of the pouring, and of the chemical character of the steel, especially as it relates to carbon.

b.—Effect of work, either by hammering or rolling.

Steel, when heated and hammered or rolled from the ingot, has its specific gravity largely increased, its strength is greatly increased, and its grain is made very fine and uniform; this is called "hammer refining," to distinguish it from the refining due to hardening.

An eminent Russian engineer has illustrated this hammer refining beautifully by comparing the hot steel to a certain solution of a salt.

If the solution be allowed to precipitate slowly and undisturbed, very large crystals will be formed, but if it be violently shaken, the crystallization is hastened and very fine crystals are formed.

So if steel be heated quite hot, but not so as to burn it, and be allowed to cool very slowly, it will form in very large, bright crystals and be very friable; but if as soon as it is hot it be taken to a heavy hammer and be thoroughly hammered by rapid and powerful blows at first, and then by lighter blows until it is of the required shape, it will be found to be very fine in grain and very strong.

Therefore, a high softening heat is consistent with good work in forging.

c.—Effects of temperature, and of changes from one temperature to another, as shown by slow cooling or rapid cooling.

The effect of heating steel which has been hammered or rolled is to increase the size of the crystals or grain, in proportion to the temperature, and to reduce the specific *gravity.* There is an apparent or real exception to this in-

crease in size of grain in steel which has been hardened from the proper temperature to produce what is known as "refining."

In this case the grain is much finer than in the bar, and in this condition any piece of hardened and tempered steel is at its best.

As this refining temperature varies with every different quantity of carbon, no rule can be laid down for determining it; it must be found by actual trial.

But there is no exception to the matter of specific gravity. The specific gravity of refined steel is less than that of the bar, although the grain is much finer. If steel be heated and cooled slowly it will be softened; that is, annealed.

If it be heated very hot, say to bright yellow, or kept hot a long time, and then cooled slowly, it will still be annealed, but it will be harsh and gritty, will not cut well, and will neither refine well when hardened nor hold a good edge when tempered. The cause of this will be obvious if we remember the experiment of the annealed chill mentioned in the earlier part of this paper. If steel be heated to different degrees, as red, bright red, orange, lemon or bright yellow color, and quenched, it will be found to be harder, more brittle, and coarser in the grain for each increasing degree of heat, after the "refining" heat has been passed. Below the "refining" heat there will be no useful degree of hardening, and the grain will be variable.

If any piece of hardened steel be heated red hot, and cooled slowly, it will be softened, the grain of the steel will return to its original appearance in the bar, and its specific gravity will be restored to the specific gravity of the bar.

This fact should put a quietus upon all quack nostrums for "restoring burnt steel."

If a piece of steel containing little carbon be alternately hardened and heated and re-hardened a number of times, it will vary in volume, but will not sustain regular increases of volume.

If steel of moderately high carbon be repeatedly hardened it will continue to increase in volume until ruptured. This will be illustrated by table No. 5.

Some years ago twelve ingots were selected by numbers, and analyzed to determine the accuracy of ocular inspection, and were afterward experimented upon in following up the search for facts in regard to the cause of "hardening."

The specific gravities of these ingots were determined, and the results were given by Prof. Langley in a paper read before the American Association for the Advancement of Science, in 1876. Since then, bars rolled from these ingots have been experimented upon, and the specific gravities of the bars and of various hardened pieces and of re-softened pieces have been determined.

These experiments will now be described.

Table I gives the analyses and specific gravities of the ingots.

Table II gives the specific gravities of six of the bars, and the specific gravities of the same bars heated to various temperatures and hardened.

Table III gives the specific gravities of the six bars, and the six hottest pieces numbered 1 in Table II, after having been annealed from the condition given in Table II.

TABLE I.

Ingot Numbers.	C.	Si.	Ph.	S.	Fe. by Difference.	Sp. Gr. Ingots.
1.....	.302	.019	.047	.018	99.614	7.855
2.....	.490	.034	.005	.016	99.455	7.836
3.....	.529	.043	.047	.018	99.363	7.841
4.....	.649	.039	.030	.012	99.270	7.829
5.....	.801	.029	.035	.016	99.119	7.838
6.....	.841	.039	.024	.010	99.086	7.824
7.....	.867	.057	.014	.018	99.044	7.819
8.....	.871	.053	.024	.012	99.040	7.818
9.....	.955	.059	.070	.016	98.900	7.813
10.....	1.005	.088	.034	.012	98.861	7.807
11.....	1.058	.120	.064	.006	98.752	7.803
12.....	1.079	.039	.044	.004	98.834	7.805

Table IV gives the specific gravities of four pieces, all from the same bar, after various treatment.

Table V gives the results of repeated hardening of three pieces of steel containing different quantities of carbon.

Consideration of the tables.

Table I contains the analysis of twelve ingots, numbered in the left hand column from 1 to 12.

The ingots were selected by the eye and numbered as in the table by Mr. Charles Parkin, with a view to varying quantities of carbon only.

It will be seen that the carbon increases with the numbers regularly, but not uniformly.

Although a repetition of the analyses of Nos. 7 and 8 confirm Prof. Langley in the correctness of his figures, it must be admitted that in this case Mr. Parkin was quite as lucky as skillful, for it is hard to believe in a really observable variation of structure due to a difference of only 0.004 *carbon.*

In the columns for Si. Ph. and S. the entire absence of progressive quantities shows clearly that these elements had nothing to do in determining the characteristic fractures.

The column of iron by difference happens to run with the carbon column, except in No. 11, where the series is broken by the abnormal amount of Si. in that ingot. Theoretically, of course, the specific gravities should run with the iron by difference, but they do not do so in ingots 3 and 5. These, however, are the only exceptions; this may have been caused by incomplete or unusually hot melting, or by hot or cold pouring, or by slow or fast pouring.

These exceptions do not vitiate the rule, and only show that no one set of experiments can be conclusive.

TABLE II.

	Sp. Gr. Pig.	Sp. Gr. Bar No. 6.	Difference.	Sp. Gr. Bar Pc. No. 5.	From Bar, Difference.	Sp. Gr. Bar No. 4.	Difference from Bar.	Sp. Gr. Bar No. 3.	Difference from Bar.	Sp. Gr. Bar No. 2.		Sp. Gr. Bar No. 1.	Difference from Bar.
3.....	7.841	7.844	.003	7.831	−.013	7.826	−.018	7.823	−.021	7.814	−.030	7.818	−.026
4.....	7.829	7.824	−.005	7.806	−.018	7 849	.025	7.830	.006	7.811	−.013	7.791	−.033
6.....	7.824	7.829	.005	7.812	−.017	7.808	−.021	7.780	−.049	7.784	−.035	7.789	−.040
8.....	7.818	7.825	.007	7.790	−.035	7.773	−.042	7.758	−.067	7.755	−.070	7.752	−.073
10.....	7.807	7.826	.019	7.812	−.014	7.789	−.037	7.755	−.071	7.749	−.077	7.744	−.082
12.....	7.805	7.825	.020	7.811	−.014	7.798	−.027	7.769	−.056	7.741	−.084	7.690	−.135

	6	5	4	3	2	1
	Not heated.	Low red heat.	Red hot.	High red.	Yellow hot.	Nearly white Scintillating.

The twelve ingots under consideration were hammered to 1¼ inch square bars at one end, and these bars were rolled to .625 diameter round bars.

Six of these bars, Nos. 3, 4, 6, 8, 10, 12, were selected for specific gravity tests; bar No. 2 was lost, or it would have *been used instead of* No. 3.

Six nicks were made around each bar at one end at intervals of about half an inch.

The six pieces were numbered from 1 at the end to 6.

Each notched bar was then heated until piece No. 1 was scintillating or nearly white hot; No. 2 was yellow hot; No. 3, high red hot; No. 4, red hot; No. 5, barely showing any red, or very low red hot; No. 6, black.

This heating was done in each case as slowly and as carefully as possible. The results show the inevitable irregularities attending only one such experiment, yet there is enough of\regularity to teach us a great deal.

As soon as the heats were obtained the bars were quenched in water.

The pieces, carefully numbered, both with the ingot numbers and with the numbers giving their order on the bars, were then broken off and sent to Prof. Langley to have the specific gravities determined. In the table the left-hand column gives the ingot numbers.

The other columns give the specific gravities of the ingots, the bars, No. 6 pieces, and of the other five hardened pieces in order, as numbered in the sketch and explained before.

The differences are, first, the difference between the Sp. Gr. of the ingots and the bars; second, the difference between the Sp. Gr. of the bar, or piece No. 6, and each piece successively.

The differences of Sp. Gr. are given in preference to the actual differences in volume, because the differences in volume run into the infinitesimals, and the mode adopted answers as well for purposes of comparison.

On comparing the ingot and bar we see a decided increase in the Sp. Gr. of the bar in every case except one, that of

No. 4. We have not discovered the reason of this anomaly. The increase in the other cases is due to hot working; this will be shown by Table IV.

It will be observed that the Sp. Gr. of the bars, except in No. 3, is nearly uniform.

This seemed very strange at first, but it is capable of a very simple explanation. The hardness of steel and its resistance to change of form increase very rapidly with an increase of carbon, and as these bars were all reduced from 3 in. square ingots to ⅝ in. round bars, it is obvious that it required much more work to reduce No. 12 than No. 4 or No. 6; therefore, as hot working increases Sp. Gr., the greater amount of work produced the greater increase in the Sp. Gr. of No. 12.

If the Sp. Gr. of the right-hand column pieces No. 1 be compared to the Sp. Gr. of the ingots, it will be seen that the relation between the numbers is entirely restored by the high heat to which the No. 1 pieces were subjected.

If the Sp. Gr. of pieces Nos. 5, 4, 3 be examined carefully, sufficient irregularities in the difference columns will be observed to show that the heating was not accomplished in regular gradations in each case, and if it were desired to lay down an exact law of variation due to differences of temperature, it would be necessary to take the mean of a great many experiments.

Nevertheless, several general laws are indicated in this table.

1. The Sp. Gr. of the ingot varies directly with the quantity of iron present.

2. The greater the quantity of carbon present, the greater *is the* amount of work necessary to produce change of form.

3. The greater the quantity of carbon present, the greater is the change in volume due to a change of temperature.

As, for example, in No. 3 the change in Sp. Gr. from the ingot to the bar is only .003, and from the same bar to the piece No. 1 the change is .026.

While in No. 12 the change in Sp. Gr. from the ingot to the bar is .020, or about seven times that in No. 3, and the change from the bar to the piece No. 1 is .135, or about five times the change in No. 3.

This is perhaps the most important observation that can be made on this series of experiments, as it shows us why it is that high steel is so much more liable to crack and break in manipulation than low steel.

We generally say one is brittle and the other is ductile; we now know that the rate of expansion per degree of temperature is much less in low steel than in high steel. Therefore, low steel is much less liable to injurious internal strains than high steel.

TABLE III.

Ingot Numbers.	Sp. Gr. of bars. No. 5.	Sp. Gr. of burned pieces. Annealed, No. 1.	Difference.
3	7.844	7.857	+.013
4	7.824	7.846	+.022
6	7.829	7.835	+.006
8	7.825	7.828	+.003
10	7.826	7.824	—.002
12	7.825	7.822	—.003

In order to settle the question of restoring "burned steel," so called, and also to determine the reverse action due to annealing, Prof. Langley took the six pieces No. 1 of Table II, and heated them all to a high yellow heat. He then allowed them to cool very slowly.

This raised a heavy scale on the pieces, which was removed by touching them on an emery wheel.

The specific gravities of these pieces were then taken, and the results are given in the table.

The restoration to the Sp. Gr. of the bar is complete, as the differences are only such as might be due to the scale on the original bars and the removal of the scale from the annealed pieces. This will be shown further in Table IV.

TABLE IV.

DRILL ROD SAMPLES.

Nos.	1 Sp. Gr.	2 Sp. Gr. Hardened.	3 Sp. Gr. Scaled and not hardnd.	Diff. 3-2 Effect of hardening.	Diff. 3-4 Effect of scale off in 1 and 2.
1.....	7.8068	7.818	7.829	—.011	+.022
2.....	7.794	7.812	7.828	—.016	+.034
3.....	7.816	7.790	7.817	—.027	+.001
4.....	7.787	7.765	7.780	—.015	—.007

It is well known that cold rolling does not increase the Sp. Gr. of iron or of steel. To ascertain the effect of cold hammering under the best conditions to increase Sp. Gr., namely, by hammering between semi-circular dies, an experiment was made, the results of which are recorded in Table IV.

A round bar, of carbon about one per cent, was operated upon.

The bar, as it came from the rolls, and unannealed, was 0.682 inch in diameter; this is No. 1 in the table.

A piece of the same bar, annealed and pickled, was 0.673 inch in diameter; this is No. 2 in the table.

The same bar twice hammered cold, after annealing, was *reduced to 0.624 inch* in diameter; this is No. 3 in the table.

The same bar annealed, and hammered cold four times, was reduced to 0.564 inch in diameter; this is No. 4 in the table.

Prof. Langley first took the Sp. Gr. of the four pieces as he received them, 1 and 2 having the roll scale upon them, and 3 and 4 being bright polished, all having been boiled in dilute potash and slowly cooled. The results are given in column No. 1.

In this case No. 3 indicates an increase of Sp. Gr. due to the cold hammering. Prof. Langley then thinking that the results might have been affected by scale in the first two pieces, next removed the scale and boiled them all in weak potash, and upon removing them from the boiling liquid cooled them rapidly by plunging them quickly into cold water.

Column No. 2 gives the results, and here we have the remarkable fact that sudden cooling from boiling temperature causes a hardening effect, which is shown more particularly in Nos. 3 and 4, where there is a decided reduction of Sp. Gr.

If subsequent trials prove this deduction to be correct, it is very important. Desiring to fortify himself as to this matter of hardening at such a temperature, Prof. Langley again boiled the pieces and allowed them to cool very slowly, thus annealing them. The results are given in column No. 3.

Here is a progressive reduction of Sp. Gr., showing that cold hammering as well as cold rolling reduces Sp. Gr. The restoration of the Sp. Gr. of 3 and 4 to the results in column No. 1 shows that there was a hardening due to quenching from boiling temperature. The column of differences 3 and 2 shows the effect of hardening. The column of differences 3 and 1 shows the effect of removing the scale. This column

also accounts for the increase of Sp. Gr. shown in the "restored" or annealed pieces of No. 1, Table I, recorded in Table III. The results recorded in Table IV have an important bearing on the inquiry into the cause of hardening, which will be shown later. They are also important as showing the entirely mercurial or thermometric nature of steel. They also indicate a mode of accurate determination of the variable rate of change of volume in steels of different composition.

It will be remembered that there is such a variable rate of change clearly shown in Table I, and further evidence will be given in Table V.

Now, by operating upon different samples by boiling, and sudden cooling in water of uniform temperature, we can get results which will range between certain uniform and known temperatures for each experiment.

TABLE V.

CHANGES IN VOLUME BY REPEATED HARDENING.

No. of times hardened.	Nos. 6 and 7, Table I. C = about .848	No. 4, Table I. C = .649.		No. 3. Table I. C = .529.	
	Contraction of hole.	Expansion.	Contraction.	Expansion.	Contraction.
1	.00172	.....	.00257	.....	.00086
2	.00172	.....	.00086	.....	.00172
3	.00688	.....	.00482	.....	.00000
4	.00688	.....	.....	.00172	.....
5	.00688	.00172	.....	.00086	.....
6	.00000	.....	.00172	.00086	.....
7	.30044 crack'd	not cracked	.00000	not cracked	.00086
Total change	.02752	.....	.00771	.00000	.00000

Hole was originally .75 diameter.

This is an experiment to find by measurement the effect of repeated hardening upon three pieces of steel containing different amounts of carbon.

A hole about .75 inch in diameter was drilled in the middle of each piece. The measurements were taken by means of a tapered plug, the difference in the distance to which it entered in each case, after the first and subsequent hardening, was measured by micrometer. The left-hand columns give the numbers of the successive hardenings. The other columns show the changes in the diameter of the hole. The first piece, of carbon .848, showed contraction of the hole every time it was hardened except the sixth, and the piece cracked at the seventh hardening. The operator supposes the sixth hardening was accidentally omitted.

The second piece, of carbon .649, showed contraction three times, then no change. Then an expansion of the hole followed by a contraction, and the seventh time there was no change. This piece did not crack.

The third piece, of carbon .529, showed two contractions, then no change, followed by three expansions, and seventh a contraction. This piece did not crack.

The total changes are quite marked:

Showing for carbon	.848	= .02752 inch.
" " "	.649	= .00771 "
" " "	.529	= .00000

This shows in another way that steel of high carbon changes more in volume per degree of temperature than steel of low carbon.

The high steel cracked, the low did not. All the pieces were of the same quality.

The experiment recorded in table No. V forms no part of the investigation by Prof. Langley and ourselves. It was

made rather crudely for a practical purpose, and the results obtained in practice confirm the figures in the table.

This ends our record of facts and brings us to—

4. A statement of some of the theories which have been given as the cause of hardening.

Perhaps the oldest, one of the most plausible, and possibly the true reason, is that unhardened steel contains carbon in graphitic and uncombined form, and hardened steel has its carbon all combined.

For proof it is stated that when unhardened steel is dissolved, the insoluble residue contains flocculent graphitic carbon; and when hardened steel is dissolved it leaves no residue of carbon; therefore, the carbon has been combined in the hardening. To answer the objection to this, that it is impossible for iron and carbon to combine in all proportions, one writer states that there is formed a definite carbide $Fe.C^4$.

That this carbide is excessively hard, and that it acts as a cement or glue, and therefore the high carbon steel becomes so much harder than the low carbon steel.

This will be conclusive after the carbide has been separated and thoroughly examined. Meantime, the hardening from boiling temperature is a little puzzling.

Another writer states that solution of the carbon takes place when the steel is heated, and that a great compression caused by the sudden contraction in cooling is the cause of hardness.

If this be so, and our experiments are correct, then carbon dissolves in steel at the temperature of boiling water.

One writer hastens to inform us that steel hardens because part of the carbon is burnt out in heating, and the rest of the *mass is compressed by* the sudden cooling. It might afford

amusement to demolish this theory, if it would not be a waste of time.

A steel-maker of twenty years' practice says hardening is caused by the carbon assuming the diamond form, in very minute crystals.

He gives, as a proof, that the hot steel decomposes water, or the cooling mixture, which always contains hydrogen.

The hydrogen combines with the carbon to form diamonds, and this is proved by the fact that the diamond and hardened steel both refract light.

In case water is the cooling medium, the hydrogen penetrates the steel to form diamonds, while the freed oxygen, conveniently inert, stays on the outside to form a thin film of oxide.

As it is well known that mercury is one of the very best cooling liquids, giving extreme hardness to steel, it is necessary to this theory to show that mercury contains hydrogen.

Again, if steel really hardens upon being quenched from boiling temperature, then water must be decomposed by that temperature.

This diamond theory is very attractive, and has received much consideration in our minds, but we are not prepared to consider it proven.

Another writer states that hardening is due to the sudden arresting of the molecular motion that exists in the heated steel, thus causing great tension and resulting hardness. He offers, as proof, that hardened steel is weaker and more brittle than unhardened steel, and cites as a very happy illustration the case of hardened glass which is known to be in a high state of tension. This theory tallies with all the facts better than any we have seen.

First, it covers all conditions, from the boiling tempera-

ture up to the high yellow heat which causes intense hardness and the brittleness of glass.

Again, it is certain that the higher the heat the greater the molecular motion. Also it is certain that from the highest heat we get the greatest hardness, and the greatest brittleness.

Finally, the restoration of grain, and of Sp. Gr. by annealing, agree well with the idea of tension in one case, and the relief from tension in the other.

It is possible, even if this tension theory be accepted as correct, that there may be, in connection with it, a change to diamond form, or from graphitic to combined carbon, and the formation of a definite carbide. Some one of these changes, taking place at a given temperature, may be just what is needed to expla: that very remarkable phenomenon known as "refining."

In mentioning a few practical considerations to be drawn from what has been said, it is hardly necessary to address the unfortunate smith and temperer; they, poor fellows, have heard so much of uniform heating and low heating, that they may well feel heart-sick, and determined to do as they please anyhow.

Let them do as they will, they will never be allowed to forget that same old cry — "too much heat" — "irregular heat"—and so on.

Let that cry continue; it has its uses; and let us look at the engineer's side.

As steel advances with irresistible steps into the field of construction, the engineer naturally asks—What am I to do with it?

Can it be worked safely?

Is it reliable?

Shall I use high steel or low?

How is it to be worked?

Is it safe to use the apparent advantages of great strength to be had in high steel?

Is it necessary to anneal finished work? etc. etc.

We think it has been clearly shown—

1. That a good soft heat is safe to use if steel be immediately and thoroughly worked.

It is a fact that good steel will endure more pounding than any iron.

2. If steel be left long in the fire it will lose its steely nature and grain, and partake of the nature of cast iron.

Steel should never be kept hot any longer than is necessary to the work to be done.

3. Steel is entirely mercurial under the action of heat, and a careful study of the tables will show that there must of necessity be an injurious internal strain created whenever two or more parts of the same piece are subjected to different temperatures.

4. It follows that when steel has been subjected to heat not absolutely uniform over the whole mass, careful annealing should be resorted to.

5. As the change of volume due to a degree of heat increases directly and rapidly with the quantity of carbon present, therefore high steel is more liable to dangerous internal strains than low steel, and great care should be exercised in the use of high steel.

6. Hot steel should always be put in a perfectly dry place of even temperature while cooling. A wet place in the floor might be sufficient to cause serious injury.

7. Never let any one fool you with the statement that his *steel possesses* a peculiar property which enables it to be

"restored" after being "burned;" no more should you waste any money on nostrums for restoring burned steel.

We have shown how to restore "overheated" steel.

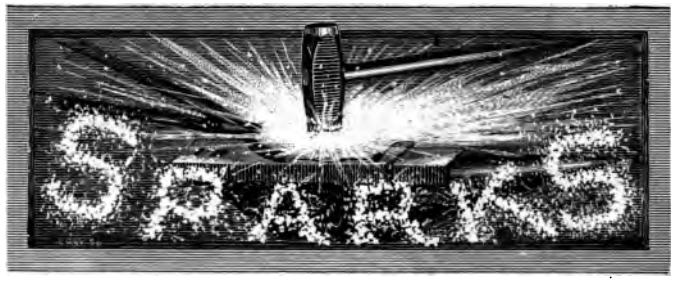
For "burned" steel, which is oxydized steel, there is only one way of restoration, and that is through the knobbling fire or the blast furnace.

"Overheating" and "restoring" should only be tried for purposes of experiment. The process is one of disintegration, and is always injurious.

8. Be careful not to overdo the annealing process; if carried too far it does great harm; and it is one of the commonest modes of destruction which the steel-maker meets in his daily troubles.

It is hard to induce the average worker in steel to believe that very little annealing is necessary, and that a very little is really more efficacious than a great deal.

Finally, it is obvious that as steel is governed by certain and invariable laws in all of the changes mentioned, which laws are not yet as clearly defined as they should be, nor as they will be; nevertheless, the fact that there are such laws should give us confidence in the use of the material, because we may be sure of reaching reliable results by the proper observance of the laws, therefore there is no good reason why engineers should be afraid to use steel if they manipulate it intelligently. Now, if we have wandered over a wide range in answer to the simple question—"Why does steel harden?"—it was necessary to have looked at many facts before we could have an intelligent opinion of many theories; and if any are in doubt as to what is the correct answer to this momentous question, we can only say that we are all in the same boat, for if you do not know, neither do we.



Overheated steel tells its own story.

A high heat opens the grain of steel and prevents refining.

Cast steel properly hardened is invariably refined thereby.

The temper of steel is regulated by percentage of carbon.

The iron used in making steel determines its quality.

Consumers of steel should be guided by makers' advices.

Sulphur is an enemy to steel.

Good fuel is essential to best results in working steel.

Charcoal, from sound wood, is the king of fuels.

Avoid exposing hot steel to draughts of air.

Pure water is a good hardening medium.

Cherry red is a safe heat for steel.

Nick cold steel with sharp chisels.

A good softening heat, for forging, can be safely used if *proper precautions* are observed.

The lead screws of lathes are often responsible for inaccuracies in the threads of taps.

Large pieces may often be protected in heating by being covered with a coating of dry clay.

No annealing is better than over-annealing.

Be sparing of the blast.

Time and care are necessary in the treatment of steel.

Burnt steel is disintegrated steel.

Properly constructed furnaces will pay for themselves in the value of tools which will be saved by their use.

"Soaking," or long continued heats, even if low, are injurious to steel.

It requires a high order of talent to treat high grade steel successfully.

In heating for hardening, great care should be taken with irregular shapes that no part of the piece be too hot.

Steel which has been annealed at a high heat will not harden on the surface.

A low red heat will anneal steel thoroughly.

Do not try to harden steel that has been annealed, before turning off the surface.

He is a good steel worker who NEVER spoilt a piece of steel.

Do not be deceived by nostrums for restoring burnt steel.

The peculiarities and proper treatment of steel are studies *for a lifetime.*

Benjamin Huntsman is said to have invented the cast steel process in 1770.

Crucible cast steel is recognized the world over as the best steel.

Low priced steel may be very dear steel.

Steel is mercurial and delicately responsive to heat; its records appear in its own structure.

The last age: the age of steel.

Dirty, slack fires put dirty sulphurous oxides on steel.

The hardening heat varies with each temper of steel, and the only safe course is to harden at the lowest heat that, on trial, is found to give the required hardness.

Hardening cracks are more often the result of uneven heating than of any defect in steel.

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